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Assessment of heavy metal contamination levels of street dust in the city of Lublin, E Poland

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Abstract

Heavy metals are constantly emitted into the environment and pose a major threat to human health, particularly in urban areas. The threat is linked to the presence of Cd, Cr, Cu, Ni, Pb, and Zn in street dust, which consists of mineral and organic particles originating from the soil, industrial emitters, motor vehicles, and fuel consumption. The study objective was to determine the level of street dust contamination with trace metals in Lublin and to indicate their potential sources of origin. The analyses were carried out with an energy-dispersive X-ray fluorescence spectrometer. The sampling sites (49) were located within the city streets characterised by varying intensity of motor traffic. The following mean content values and their variation (SD) were determined: Cd: 5.1 ± 1.7 mg kg^{-1}, Cr: 86.4 ± 23.3 mg kg^{-1}, Cu: 81.6 ± 69.2 mg kg^{-1}, Ni: 16.5 ± 3.9 mg kg^{-1}, Pb: 44.1 ± 16.4 mg kg^{-1}, and Zn: 241.1 ± 94.6 mg kg^{-1}. The level of pollution was assessed with several widely used geochemical indices (geoaccumulation index, enrichment factor, pollution index, index of ecological risk, and potential ecological risk index). For most of the indices, the mean (median) values are arranged in the following manner: Zn > Cu(or Cd) > Pb > Ni > Cr. In general, street dust in Lublin does not show pollution with Cr, Ni, and Pb. I_{geo} and EF indices show moderate levels for Cu, Cd, and Zn; their presence in street dust is linked with anthropogenic factors (motor traffic). A significant threat is posed by Cd, and more than half of the samples show considerable pollution with cadmium (median for the index of ecological risk: 151). The spatial pattern of indices and the results of statistical analyses (CA, PCA) indicate three groups of elements: (1) Cr and Ni: natural origin; (2) Pb: mixed origin; and (3) Cd, Cu, and Zn: anthropogenic origin (mainly motor vehicle traffic). Higher content values for metals of anthropogenic origin in street dust indicate that it is a source of pollution of soil and air in the city.

Keywords Heavy metals · Pollution indices · Street dust

Introduction

Street dust is a major source of air and soil contamination in cities (Charlesworth et al. 2011). It consists of mineral and organic particles accumulating on the surface of roads and originating from industrial emitters, motor traffic, and natural sources. In Poland, mineral material and chemical compounds originating from the sand used to keep the roads clear in winter constitute a considerable part of street dust as well. Thus, the main components of street dust are common minerals such as quartz or feldspars. It also contains

various kinds of toxic compounds, including heavy metals. Their main sources are car exhaust emission and the wear and tear of various vehicle parts (tyres, brake discs) (Bilos et al. 2001; Manno et al. 2006; Lu et al. 2010). Pollutants accumulating in street dust are exceptionally hazardous due to the possibility of their secondary emission and occurrence at low height, in the living zone of humans, plants, and animals. Heavy metals can thus penetrate into the human body and pose a grave threat to human health (Aeolian et al. 2008; Zheng et al. 2010; Charlesworth et al. 2011).

In the past, increased lead content was observed in the soils on the sides of roads with high traffic intensity. Other metals also occur here: zinc, cadmium, chromium, nickel, and vanadium. Lead is removed from the atmosphere by the rain and snow (Charlesworth et al. 2011). Alongside lead from fuel consumption, increased concentrations of cadmium, cooper, and zinc occur in roadside soils (De Miguel

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et al. 1997). These metals originate from emissions related to motor traffic and dust produced by the wear and tear of car tyres (zinc oxide is added to rubber during vulcanization). The main source of soil pollution with chromium is its emissions into the atmosphere as a result of coal burning and chrome steel manufacturing (Amato et al. 2011).

Investigations conducted in many cities indicate increased concentrations of trace elements in street dust (e.g., Ahmed and Ishiga 2006; Han et al. 2006; Shi and Wing 2013). It should be stressed that such studies are usually conducted in large and very large cities characterised by a considerable intensity of motor traffic (e.g., Du et al. 2013; Li and Liu 2001; Sezgin et al. 2003; Zhao et al. 2015).

Pollution of street dust with heavy metals is not discussed particularly often in Poland. Few studies on trace-element content in street dust have been published so far (e.g., Walczak 2010; Piontek et al. 2012; Kozanecka et al. 2003). The contamination of soils in the vicinity of transport routes has been discussed much more frequently (e.g., Czarnowska et al. 2002; Klimowicz and Melke 2000; Pasieczna 2003; Plak et al. 2010). No studies have been undertaken so far with regard to a comprehensive index-based assessment of street dust pollution with heavy metals in cities.

Soils in the city of Lublin were studied in the past and the results do not show considerable levels of pollution with heavy metals (Pasieczna 2003; Plak et al. 2010). The same applies to the pollution levels in water sediments (Zgłobicki et al. 2011). However, heavy metals in Lublin's street dust washed away during rainfall and snowmelt accumulate in water sediments in the Bystrzyca river valley downstream of the city (Zgłobicki et al. 2016). This primarily concerns Cd, whose higher levels had already been found in the valley before (Bojakowska and Sokołowska 1996).

The study objective was to assess the level of street dust pollution with heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) and to determine the role of human impact on the spatial variation of pollution in Lublin, a medium-sized city located in E Poland. The study will make it possible to estimate the occurrence of pollution threatening residents' health also in medium-sized cities as well as the reason for it. It is the fist study of this kind in Poland. The metals chosen for analysis are commonly regarded as indices of air pollution linked to motor vehicle traffic and industrial emissions in urban areas (De Miguel et al. 1997; Kabata-Pendias and Pendias 1997; Charlesworth et al. 2011).

Materials and methods

Study area

Lublin is located in eastern Poland (51°08′23.31″–51°17′47.61″N, 22°27′15.41″–22°40′24.75″E)
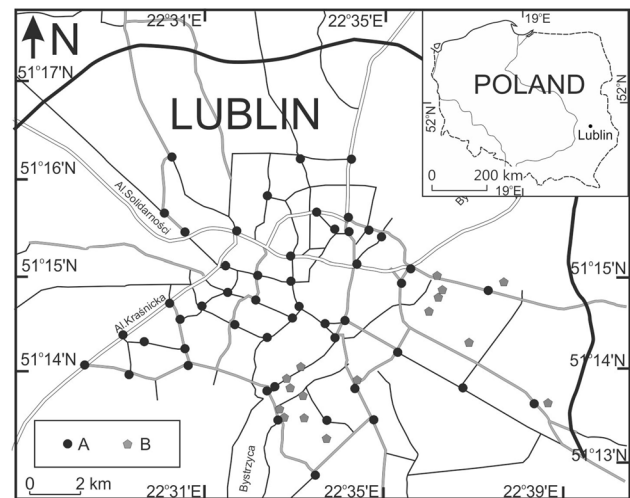

Fig. 1 Location of Lublin. 1—sampling sites, 2—small and medium industrial plants

(Fig. 1). It covers an area of 147.5 km², inhabited by nearly 350 thousand people. Most industrial areas are located in the eastern part of the city. Major industrial facilities include the Lublin–Wrotków heat and power generating plant, URSUS factory and Sipma agricultural machine factory. Numerous food industry plants as well as pharmaceutical, chemical, and construction enterprises operate here as well.

The physical geography of the city is varied. The western part is characterised by a varied land relief associated with the loess cover. A dense network of deep, dry valleys connected with larger, permanently drained valleys occurs here, and the elevation differences reach 40 m. In the other parts of the city, the differences are much smaller (up to a dozen or so metres). The river system of Lublin consists of Bystrzyca and its tributaries: left hand—Czechówka (flowing west to east) and right hand—Czerniejówka (flowing south to north). These are medium-length rivers (20–70 km). The mean annual temperature in Lublin is + 8.0 °C. The mean annual precipitation volume is approx. 650 mm. The mean wind speed in Lublin is not high: 2.7 m s⁻¹. There is a clear predominance of southerly and westerly winds (S, SW, W). The dominant soil types are Luvisols and Cambisols developed on loess in the western part of the city; alluvial soils in the Bystrzyca valley as well as Cambisols and podzolic soils in the eastern part.

Data collection

In the study, the levels of heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) were analysed in the street dust sampled along roadways in Lublin. The concentration of reference elements Mn and Fe was also determined. Samples were collected from a total of 49 points located within the main roads characterised

by varying intensity of motor traffic. Most of them were situated in the immediate vicinity of junctions, i.e., in locations with increased exhaust emission.

The study material originated from the surface of streets and was sampled in places of dust accumulation along the edges of streets. Samples were collected once, in March 2014. They were collected by sweeping up 500 g of material with a polyethylene brush and dustpan into plastic bags, then dried at room temperature and put through a 100 μm sieve. The preparations for analysis were done in the form of tablets of pressed material (10 g sample and 1 g wax) ground in a zirconia ball mill (Micro Mill). The analyses were carried out with an energy-dispersive X-ray fluorescence spectrometer (EDXRF, Epsilon5 Panalytical). Each sample was analysed three times, and metal content was calculated as the mean of three measurements. The accuracy of determinations was verified using reference material NCS DC 73385 (five measurements) with certified content of the elements studied: $Cd = 2$ mg kg^{-1}, $Cr = 370$ mg kg^{-1}, $Cu = 40$ mg kg^{-1}, $Ni = 64$ mg kg^{-1}, $Pb = 58$ mg kg^{-1}, and $Zn = 210$ mg kg^{-1}. Measurement error 3–5%. The range of measured values: Cd—1.9–2.08 mg kg^{-1}, Cr—342.3–351.3 mg kg^{-1}, Cu—39.7–4.8 mg kg^{-1}, Ni—60.1–64.9 mg kg^{-1}, Pb—58.7–59.3 mg kg^{-1}, and Zn—213.6–218.6 mg kg^{-1}.

Road traffic intensity data were available for some of these sampling sites. Based on this data as well as information on the distribution of industrial plants, road parameters (number of lanes and presence of junctions), the sampling sites were divided into four categories: (1) side streets; (2) main streets of the city; (3) main exit roads; and (4) roads in the industrial district.

To determine the geochemical background, the material originating from the soils (parent material) in unpolluted agricultural areas surrounding the city was also analysed. The chemical composition of ten soil samples was determined. This enabled the identification of natural heavy metal levels in the vicinity of Lublin by means of the same method of concentration measurement. Sampling sites are located a few kilometres (about 5 km) from the borders of the city.

Environmental pollution indices

Based on the data obtained, the indices (commonly used in literature) showing the degree of environmental pollution with heavy metals and the related threats were calculated: geoaccumulation index (I_{geo}), enrichment factor (EF), pollution index (Pi), index of ecological risk (Er_i), and potential ecological risk index (RI) (Müller 1979; Håkanson 1980; Ergin et al. 1991). To identify groups of elements differing in terms of their origin, the following statistical methods were used: correlation analysis, principal component analysis (PCA), and cluster analysis (CA).

The geoaccumulation index is defined by the following formula:

$$I_{geo} = \log_2\left(C_n \big/ 1.5\, C_{ref} \right),$$

where C_n denotes the concentration of the metal, and C_{ref} denotes the value of the background. Six categories of pollution are distinguished (Müller 1979): unpolluted ($I_{geo} < 0$), unpolluted to moderately polluted ($I_{geo} = 0$–1), moderately polluted ($I_{geo} = 1$–2), moderately to strongly polluted ($I_{geo} = 2$–3), highly polluted ($I_{geo} = 3$–4), highly to extremely polluted ($I_{geo} = 4$–5), and extremely polluted ($I_{geo} > 5$).

Enrichment factor is calculated with the following formula:

$$EF = \frac{C_n / C_{ref}}{B_n / B_{ref}},$$

where C_n is the metal concentration in a sample, C_{ref} is the background value for the metal under study, and B_n is the reference metal concentration in the sample. In this study, Mn was used as a reference element. B_{ref} is the background value for the reference metal. Five categories of pollution are distinguished (Ergin et al. 1991): minimal (EF < 2), moderate (EF = 2–5), significant (EF = 5–20), very high (EF = 20–40), and extreme (EF > 40).

Pollution index (Pi) can be defined with the following formula:

$$Pi = \frac{C_n}{C_{ref}}.$$

See the explanation of the indices above; pollution categories after Shi and Wang (2013): unpolluted (Pi < 1), low pollution (Pi = 1–2), moderate pollution (Pi = 2–3), and high pollution (Pi > 3).

The index of ecological risk factor is defined with the following formula:

$$Er_i = T_i \times \frac{C_n}{C_{ref}},$$

where T_1 is the toxic-response factor for the metal. The particular metals show varying degrees of toxicity to humans. Håkanson (1980) provides the following values for this index: Cd—30, Cr—2, Cu—5, Ni—5, Pb—5, and Zn—1. Five categories of pollution are distinguished: low (< 40), moderate (Er_i = 40–80), considerable (Er_i = 80–160), high (Er_i = 160–320), and very high (> 320).

Potential ecological risk (RI) is defined as the sum of the index of ecological risk factors (Er_i) for metals in a given sample (Soliman et al. 2015). Four categories of the index are distinguished (Håkanson 1980): low (RI < 150), moderate (RI = 150–300), considerable (RI = 300–600), and high (RI > 600).

Data analysis

To identify the origin of the elements, statistical methods were used that enabled to assign the studied elements into groups characterised by similar spatial variation patterns. The investigations included the content of Fe and Mn which show a slight enrichment in relation with the geochemical background. The following methods were used in data analysis: (1) Pearson's correlation coefficient analysis; (2) principal component analysis (PCA); and (3) cluster analysis (CA). The data for all types of analyses were normalised to the geochemical background values. The normalisation of this kind was necessary, because the natural content of elements varies a lot. Thanks to normalisation, it was possible to avoid the distortion of the results by elements with a high natural content in the soil.

PCA makes it possible to analyse a data set for mutual relationships and generate substitute parameters, i.e., the principal components. The principal components consist of groups of several mutually correlated elements, which reduces the number of independent variables, making it easier to analyse them. The relationships between data are mathematical, but they allow for several practical conclusions. For instance, it can be supposed that the mutually correlated elements constitute a group of elements with a similar origin.

CA enables the determination of geometric, multidimensional Euclidean distances between the specific elements. Thus, the results can confirm the PCA results, but they can also yield additional, multidimensional information on the mutual relationships of data. The distances between data points were analysed using Ward's method.

Results

Heavy metal content in street dust

For most of the sites under study, the motor traffic intensity ranges from 50 to 1500 cars per hour (Fig. 2). Mean heavy metal levels in street dust can be arranged in the following order: $Zn > Cr > Cu > Pb > Ni > Cd$. In the case of maximum concentration levels, the order is the same. Mean concentrations, normalised to the background values, are in the following order: $Zn > Cu > Cd > Pb > Ni > Cr > Mn > Fe$. The geochemical background was exceeded most in the case of Cd, Cu, and Zn (5–6 times on average), while the mean levels of Cr, Ni, and Pb were about twice as high as the geochemical background (Table 6). In the case of maximum concentrations, the index was: Cd—14, Cr—6.7, Cu—31, Ni—2.5, Pb—6.7, and Zn—14.9. A high variation of the content of the studied metals in street dust was found. The variation was the highest for Cu (VC > 50, a high level of
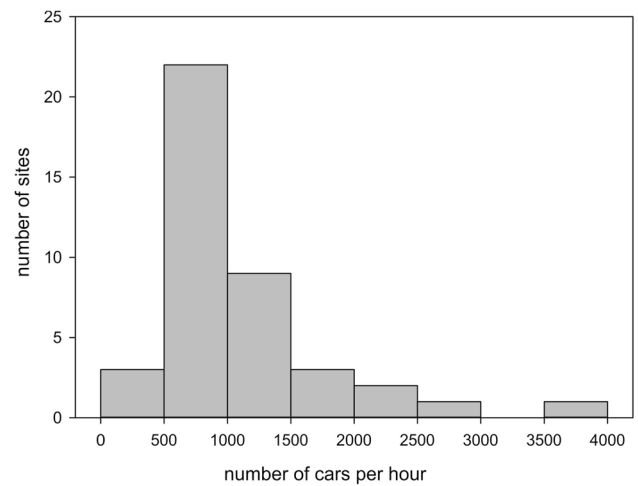

Fig. 2 Intensity of road traffic in selected sampling sites

Table 1 Content of heavy metals in road dust in Lublin (mg kg^{-1})

	Mean value (± SD)	Range	Variation coefficient (VC) (%)	Geochemical background
Cd	5.1 ± 1.7	3.0–14.1	33	1.0
Cr	86.4 ± 23.3	35.1–175.2	26	50.0
Cu	81.6 ± 69.2	21.6–496.7	78	16.5
Ni	16.5 ± 3.9	1.4–23.9	22	9.5
Pb	44.1 ± 16.4	21.5–131.2	36	19.6
Zn	241.1 ± 34	73.3–589	34	39.4

variation), clearly lower for Cd, Pb, and Zn (20 < VC < 40, a medium level of variation), and the lowest for Cr and Ni (Table 1). The higher the VC value, the higher the anthropogenic impact (Martin et al. 2006).

The lowest heavy metal content levels occur in samples collected from the side streets; they are slightly higher in the case of the main roads, and the highest for exit roads from the city (particularly Cd, Cr, and Cu contents) and roads in the industrial district (where Ni, Pb, and Zn show the highest levels) (Table 2). The highest variation was found for Cu, the mean values for the main roads are nearly twice as high as for the side streets. In the case of Cd, Pb and Zn, the value of this index was about 1.5. Cr and Ni showed the lowest variation of concentration in relation with the location of the sample collection sites. This indicates an intense anthropogenic impact on the content of the particular elements: it is the highest for Cu, and the lowest for Cr and Ni.

Statistical analysis

The significance level of the correlation is very high; for most data pairs, it is lower than 0.001 and for the remaining

Table 2 Spatial variation of metals in road dust in Lublin

	Cd	Cr	Cu	Ni	Pb	Zn
	Mean content (maximum content) (mg kg^{-1})					
Side streets	4.5 (5.1)	83.7 (124.5)	65.6 (144.8)	14.4 (22.9)	37.9 (50.7)	188.5 (290.7)
Main streets of the city	4.8 (6.0)	83.9 (103.6)	88.5 (172.6)	17.1 (21.7)	43.0 (67.1)	250.4 (427.9)
Main exit roads	6.7 (14.1)	94.1 (175.2)	130.1 (496.8)	17.6 (23.7)	46.1 (75.9)	291.4 (589.2)
Roads in the industrial district	5.2 (6.6)	97.8 (147.6)	80.8 (116.1)	18.8 (23.9)	59.1 (131.2)	293.7 (395.8)

Table 3 Correlation matrix for metal concentrations in road dust samples (Pearson correlation coefficients and p values)

	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Cd	1	0.649	0.887	0.813	0.673	0.494	0.357	0.722
Cr	$p<0.001$	1	0.697	0.811	0.728	0.627	0.459	0.709
Cu	$p<0.001$	$p<0.001$	1	0.815	0.632	0.507	0.352	0.740
Fe	$p<0.001$	$p<0.001$	$p<0.001$	1	0.918	0.856	0.559	0.898
Mn	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	1	0.878	0.539	0.788
Ni	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	1	0.507	0.771
Pb	$p=0.012$	$p=0.001$	$p=0.013$	$p<0.001$	$p<0.001$	$p<0.001$	1	0.606
Zn	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	1

Table 4 Three principal components and eigenvectors influencing them

	Factor 1	Factor 2	Factor 3
Cd	**− 0.829**	**0.453**	− 0.152
Cr	**− 0.839**	0.080	0.029
Cu	**− 0.834**	**0.464**	− 0.156
Fe	**− 0.986**	0.011	0.091
Pb	**− 0.622**	**− 0.552**	**− 0.547**
Mn	**− 0.911**	− 0.169	0.243
Ni	**− 0.835**	− 0.339	0.372
Zn	**− 0.920**	− 0.064	− 0.054
Variation percentage (%)	**72.822**	**11.017**	**6.969**
Total variance (%)	**72.822**	**83.84**	**90.81**

Bold values indicate statistically important impact (0.0–0.2—no impact; 0.2–0.4—low impact; 0.4–0.7—moderate impact; 0.7–0.9—strong impact; 0.9–1.0—very strong impact)

eigenvectors on each of the principal components, percentage of variance explained by each of the first three principal components, and total variance explained by the principal components. Component 1 accounting for 72.8% of the total variance, having high loadings on the all metals, indicates the impact of natural and anthropogenic sources. It seems, however, that the main role is played by the delivery related to the deposition of soil dust and mineral material used to keep the roads clear in winter. Component 2 explains 11.0% of the variance, which had high loadings on Cu and Cd. These metals are related to vehicle emissions. Factor 3 accounts for 6.9% of the total variance and presents high loadings on Pb, and its delivery is related to anthropogenic and natural impact.

Based on PCA, four groups can be distinguished and treated as elements with a similar origin: anthropogenic, natural, or mixed. The first group consists of Cr, Ni, Zn, Cr, Mn, and Fe, and it can be regarded as a natural group. Cu and Cd belong to the second group, and Pb to the third group. The analysis of further principal components (fifth) shows that Zn can be assigned to a separate group.

The results of the cluster analysis yield a slightly different image than the PCA: they indicate the existence of two main group of metals probably originating from different sources (Fig. 3). The first group consists of Cr, Ni, and Mn as well as Fe and Pb. The origin of these elements in street dust can be linked mainly with natural factors; the human impact seems to increase in the following order: (Mn, Cr, Ni) < Fe < Pb. The second group consists of elements, whose delivery to street dust is of anthropogenic origin. The greatest delivery occurs for Cu that forms a separate sub-group.
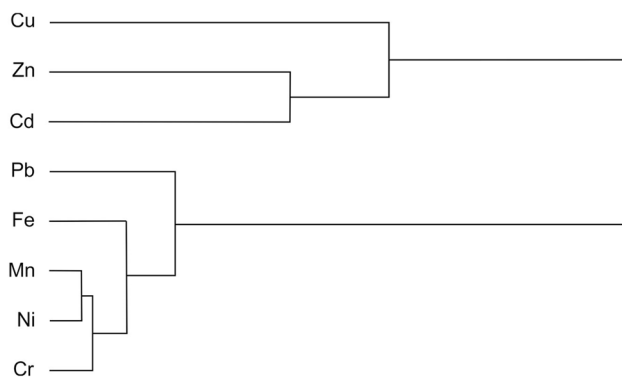
data is lower than 0.05 (Table 3). In this case, the correlations of Pb content with other data content levels are weak or medium. Fe and Zn show high correlations with all elements (except Pb). Mn correlates with Cr, Fe, Ni, and Zn. Strong correlations also occur between Cu and Cd, Fe, and Zn as well as between Ni and Fe, Mn, and Zn. On this basis, it is possible to distinguish the following groups of elements between which correlations occur: (1) Cu and Cd; (2) Pb; and (3) Cr, Fe, Mn, Ni, and Zn.

Table 4 shows a fragment of the matrix of eigenvectors and presents PCA results: three principal components jointly accounting for more than 90% of the variance, influence of

Fig. 3 Results of cluster analysis, using Ward's method, for data normalised to the background values

The statistical analyses used (PCA, CA and data correlation) as well as the relationships between concentrations with the geochemical background showed that the analysed elements form distinct groups that can be interpreted as groups with a different origin of the analysed elements. The results of the methods used partially confirm one another. Based on the analyses, two groups can be distinguished: (a) Cr, Mn, Ni, and Fe: group of elements of natural origin and (b) Cu and Cd: elements of anthropogenic origin. In the case of Pb and Zn, their assignment to a specific group, based on the results of the analyses above, is not unequivocal. This is most probably a result of the fact that the origin of Pb is linked with natural factors (as indicated by data deviation from the geochemical background of this element), the origin of Zn is anthropogenic, while the origin of the other elements is largely (though less than in the case of Pb and Zn) anthropogenic or natural.

Pollution indexes

The geoaccumulation index showed considerable spatial diversity (Fig. 4). In the case of Cd, most of the samples belonged to the moderately polluted category, while samples obtained from the exit roads from the city belonged to the moderately to strongly polluted category (2.1–2.5). In the case of Cr and Ni, the street dust samples were not polluted or belonged to the unpolluted to moderately polluted category (0.1–0.9). A high variation occurred in the case of Cu: most dust samples belonged to the moderately polluted category, but some samples also belonged to the unpolluted as well as highly to extremely polluted category (maximum level: 4.3). The index reached the highest level along the main exit road and in the city centre. In the case of Pb, all dust samples except for one belonged to the unpolluted to moderately polluted category (0.05–0.98). Quite a significant spatial variation of the geoaccumulation index occurred also for Zn: most samples belonged to the moderately to

strongly polluted category (2.08–2.85), and 14 to the moderately polluted category (Table 5).

The pollution index shows relatively high levels of pollution with the studied elements. The samples are characterised by a high level of pollution with Cd, Cu, and Zn, moderate and low pollution with Pb as well as low and moderate pollution with Cr and Ni (Table 5).

All Cr, Ni, and Pb samples were characterised by a minimum level of enrichment (EF < 2) (Fig. 4; Table 5). In the case of Pb, one sample, collected in the industrial district, showed a moderate level of enrichment. For Cd, Cu, and Zn, the enrichment factors were higher and usually ranged between 2 and 5 (moderate). At nine sites located in the eastern part of the city (the industrial district), Zn had a considerable level of enrichment (5.02–6.45). This factor reached a slightly higher level for Cu in the same sample (12.9). A considerable level of enrichment for Cu occurred in four samples collected in a major thoroughfare with a high intensity of trolleybus traffic. A minimum enrichment with this element (1.59–1.93) was found in the northern part of the city. Maximum levels above 3 (Cd, Cu, Pb i Zn) indicate anthropogenic pollution (Han et al. 2006).

Low levels (< 40) of the potential ecological risk index for Cr, Ni, Pb, and Zn were found in all samples. In the case of Cu, the occurrence of moderate risk was found in six samples and high risk (15.5) in one sample. These samples were collected along one of the main thoroughfares. This index reached the highest levels for Cd; it was higher than 150 for more than half of the investigated locations, and the levels were in the high category (161–252) in 18 samples. The highest level (423) found in one sample places the sample in the very high potential ecological risk category (Fig. 4). A vast majority of samples with the highest levels of this index were located within thoroughfares with a high intensity of traffic, including heavy vehicle traffic (Table 5).

Most of the studied samples belong to the moderate potential ecological risk category (total index for all metals). At four locations, i.e., streets with a low intensity of traffic, the low category occurred (111–149). Considerable potential ecological risk was determined (304–352) at three locations along the main thoroughfare of the city. The highest level of this index was 626 (high potential ecological risk) (Fig. 5).

Discussion

Heavy metal content in street dust and upper soil horizons in cities is originated from various forms of human activity—operation of industrial plants, fuel consumption, exhaust emissions, and the wear of various vehicle parts (Al-Khashman 2013; Bilos et al. 2001). Cu is commonly used in vehicle oils (Al-Khashman 2004). It can also be produced as a result of the wear of motor oil pumps, corrosion of metal
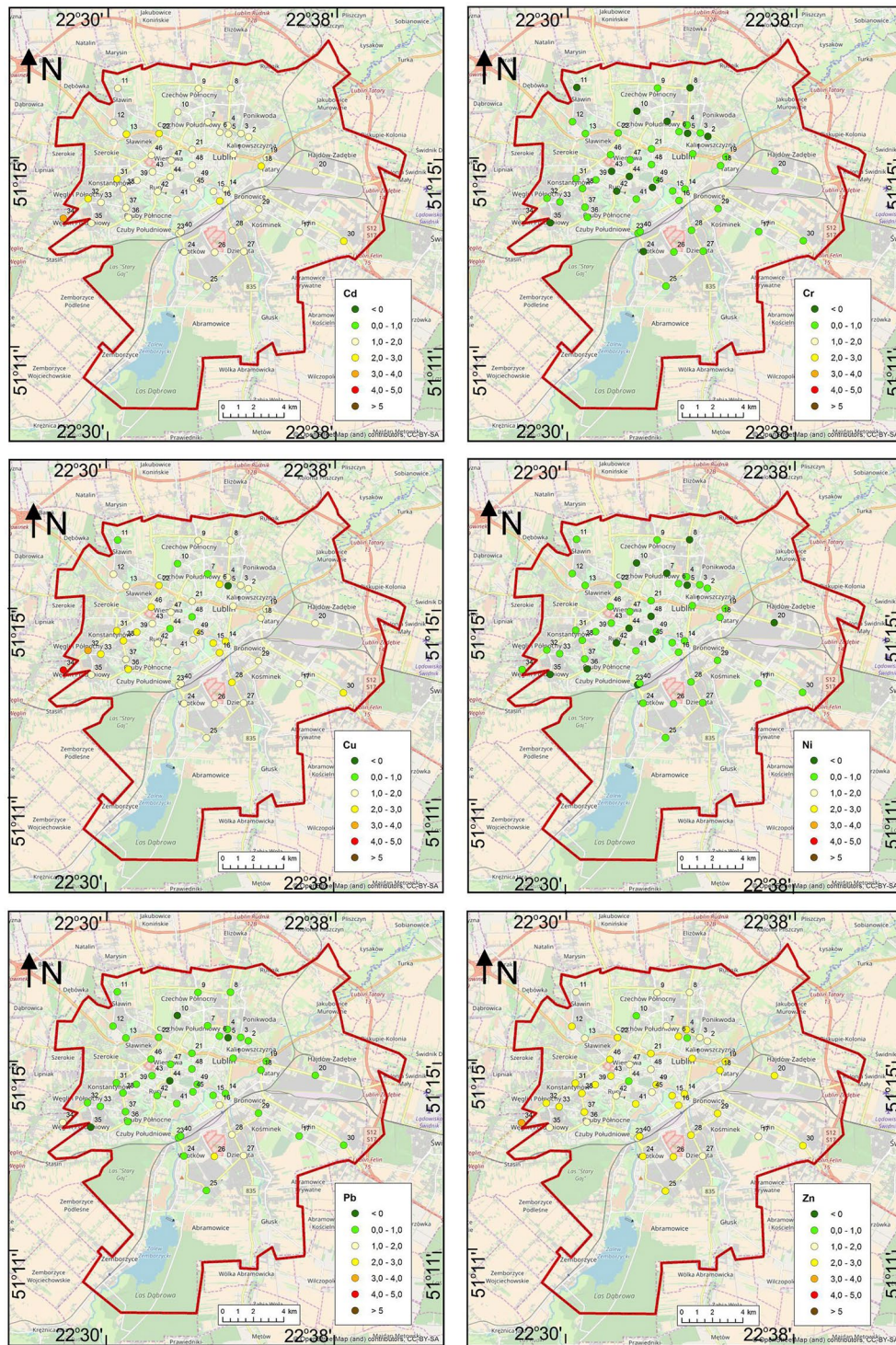
Fig. 4 Spatial diversity of the I_{geo} index for the heavy metals under study; unpolluted ($I_{geo} < 0$), unpolluted to moderately polluted ($I_{geo} = 0–1$), moderately polluted ($I_{geo} = 1–2$), moderately to strongly polluted ($I_{geo} = 2–3$), highly polluted ($I_{geo} = 3–4$), highly to extremely polluted ($I_{geo} = 4–5$), and extremely polluted ($I_{geo} > 5$)

car parts in contact with the oil (De Miguel 1997) as well as engine wear and tear (Al-Khashman 2007; Jaradat and Momani 1999). The pollution of soils and street dust with

Zn is linked to the wear of the moving car parts, for example, tyre wear could be an important source of this metal in street dust (Friedlander 1973; Al-Khashman 2004). Plak

Table 5 Level of street dust pollution based on pollution indices—mean values (in brackets classes of pollution)

	Cd	Cr	Cu	Ni	Pb	Zn
Geoaccumulation index						
Min	1.03 (II)	− 1.09 (I)	− 0.19 (I)	− 1.34 (I)	− 0.43 (I)	0.31 (II)
Max	3.23 (V)	1.22 (III)	4.32 (VI)	0.75 (II)	2.15 (IV)	3.33 (V)
Median	1.75 (III)	0.21 (II)	1.84 (II)	0.28 (I)	0.60 (I)	2.2 (III)
Enrichment factor						
Min	1.87 (I)	0.75 (I)	1.59 (I)	0.74 (I)	0.96 (I)	2.24 (II)
Max	6.08 (III)	1.72 (I)	12.98 (III)	1.36 (I)	3.78 (II)	6.45 (III)
Median	3.17 (II)	1.06 (I)	2.93 (II)	1.10 (I)	1.38 (I)	3.93 (II)
Pollution index						
Min	3.0 (III)	0.70 (I)	1.31 (II)	0.59 (I)	1.22 (II)	1.86 (II)
Max	14.1 (IV)	3.50 (III)	30.1 (IV)	2.51 (III)	3.87 (IV)	14.95 (IV)
Median	5.05 (IV)	1.74 (II)	5.37 (IV)	1.83 (II)	2.27 (III)	7.03 (IV)
Index of ecological risk						
Min	92.25 (III)	1.40 (I)	6.56 (I)	2.95 (I)	5.55 (I)	1.86 (I)
Max	423.12 (IV)	7.00 (I)	150.53 (III)	12.59 (I)	33.47 (I)	14.95 (I)
Median	151.53 (III)	3.48 (I)	26.87 (I)	9.15 (I)	11.36 (I)	7.03 (I)

Fig. 5 Spatial diversity variation of the potential ecological risk index: low (RI < 150), moderate (RI = 150–300), considerable (RI = 300–600), and high (RI > 600)
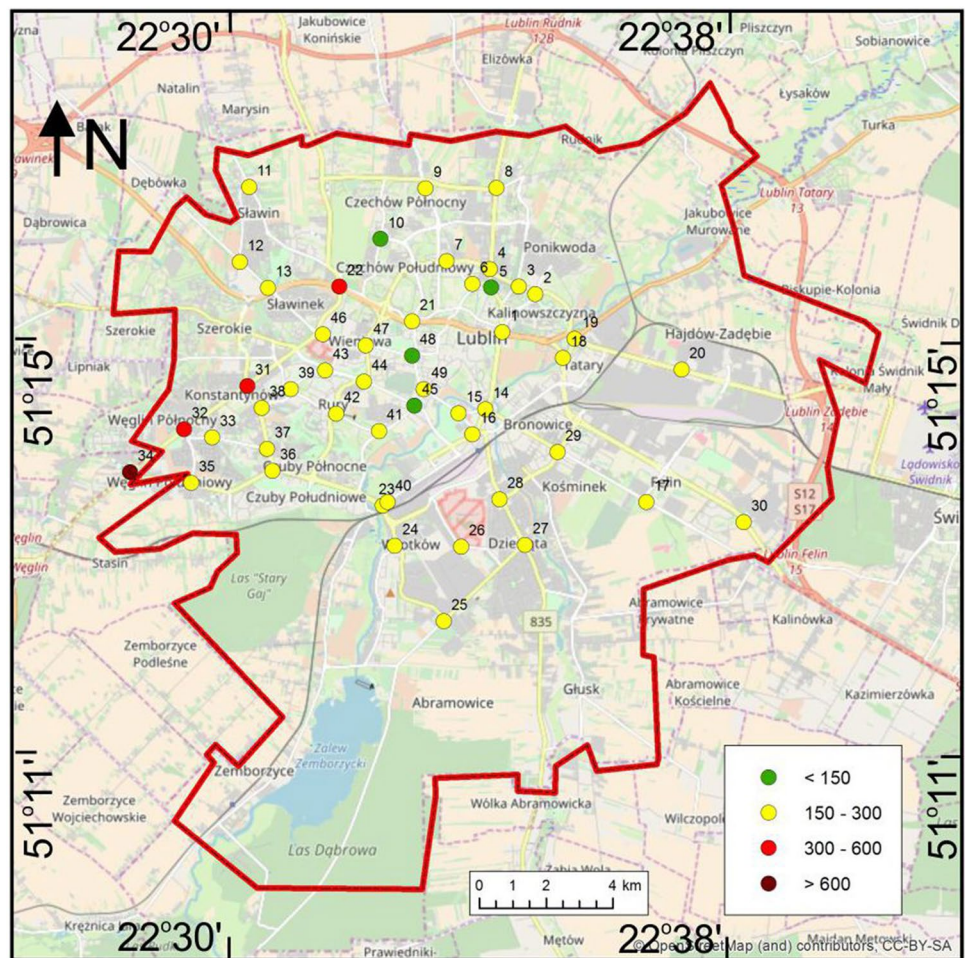
et al. (2010) also point out that higher Cu concentrations in the soils in Lublin result from the use of aboveground copper wires powering the trolleybuses. Increased Cd levels in street dust are also linked with road traffic emissions (Divrikli et al. 2005). In the case of Lublin, increased Cd levels in street dust were found within two main thoroughfares (Fig. 4), characterised by high heavy vehicle traffic. Coal-fired furnaces, still used to heat private homes in the city, are another source of Cd. Its increased levels occurred in areas, where this kind of homes predominates. The greatest contamination with Zn was found in the eastern part of the city, where an automotive factory existed in the past.

The elements described in this study show varying toxicity for humans. Cd is the most toxic element that can be absorbed by the respiratory system and can reside in the human body for a long time. The toxic effect of Cd consists of kidney dysfunction, neoplastic transformations, and hypertension. The toxicity of Cu, Ni, and Pb is lower, but humans are susceptible to the bioaccumulation of these elements absorbed into the body through the respiratory system (Kabata-Pendias and Pendias 1999). Increased levels were found only in the case of Cu; hence, this element may pose a threat to residents. Copper leads to oxidative cell damage and causes neuron disorders (Gaetle and Chow 2003).

Cd, Cr, Cu, Ni, Pb, and Zn content levels are similar to the levels found in other cities in Europe and North America with a similar population size. Only the mean concentrations for Cd are clearly higher than in Tallinn or Coventry. In the case of other elements, their content levels are usually lower (Table 6).

The calculated indices show varying levels of street dust pollution. In the case of the geoaccumulation index and pollution index, the mean values follow this order: Zn > Cu > Cd > Pb > Ni > Cr. A similar situation occurs in the case of the enrichment factor but the mean index for Cd is higher than for Cu. Due to the varying toxicity of the studied elements, a distinctly different order occurs in the case of the index of ecological risk: Cd > Cu > Pb > Ni > Cr > Zn. Indices such as I_{geo} and EF indicate a moderate contamination/enrichment of street dust with Cd, Cu, and Zn. The pollution index for these elements places them in the high pollution category. In the case of the other metals, all indices indicate a lack of pollution or low pollution with Cr, Ni,

and Pb. The index of ecological risk shows a considerable level of pollution only for Cd. Similar to other studies, this study did not find increased Pb levels in street dust (Yeung et al. 2003). In the past, this element was the main pollution index, but owing to the common use of unleaded petrol, exhaust fumes ceased to be the main source of Pb in the air (De Miguel et al. 1997).

A comparison of the obtained results concerning environmental pollution indices indicates a similar level of pollution even in the case of cities with a distinctly greater population and higher number of industrial plants (Al-Khashman 2013; Shi and Wang 2013; Gope et al. 2017; Han and Lu 2017). The contamination of street dust in Lublin with Cd is distinctly higher than that reported for cities in the Middle East and China. However, it was not as high as, for example, in Kuala Lumpur, where the maximum EF for Cd in the < 125 μm fraction was 16.5 (Han et al. 2014). High EF values for Pb are also reported by Al-Khashman (2013) for the city of Ma'an (Jordan). It should be stressed, however, that in both cases, the authors used a different method of determining this index: the reference value that they adopted was the content of the element in the Earth's crust, which is distinctly lower than content in reference soils. This shows the difficulty of directly comparing results obtained for various cities. The main challenge here is the method of determining the geochemical background that plays a key role in the case of some pollution indices.

Permissible levels of heavy metal content in street dust have not been established so far, and it is inappropriate to compare the obtained values directly with such standards for soil or air. In general, however, it can be concluded that mean content values are lower than those indicated for agriculturally used soils in Poland: Cd—4 km kg^{-1}, Cr—150 mg kg^{-1}, Cu—150 mg kg^{-1}, Ni—100 mg kg^{-1}, Pb—100 mg kg^{-1}, and Zn—300 mg kg^{-1} (Kabata-Pendias and Pendias 1999). It should be remembered, however, that in the case of soils, metals are immobilised to some extent and can be absorbed in the human body mainly through food, i.e., plants that have taken up these metals from the soil. In the case of street dust, on the other hand, heavy metals can be released by air mass movement and absorbed directly by the

Table 6 Heavy metal content in cities around the world

Location	Population	Cd	Cr	Cu	Ni	Pb	Zn	Sources
Lublin	350,000	5.1	86.4	81.6	16.5	44.1	241.1	Present study
Warsaw	1,700,000	–	–	31	10	34	64	Kazanecka et al. (2003)
Zielona Góra	140,000	0.2–9.7	–	12–264	–	–	20–409	Walczak (2010)
Oslo	630,000	1.4	–	123	41	180	412	De Miguel et al. (1997)
Coventry	300,000	0.9	–	226	130	47	386	Charlesworth et al. (2003)
Hamilton	500,000	4.0	–	129	–	214	645	Droppo et al. (1998)

respiratory system. Therefore, even lower levels of heavy metals can be harmful.

As it could be expected, street dust is much more polluted with heavy metals than soils in Lublin (Pasieczna 2003). The ratios of their mean content in street dust to their mean content in the city's soils are as follows: Cd 10:1, Cr 10:1, Cu 10:1, Pb 3:1, and Zn 6:1. Their higher levels in soils in the vicinity of streets indicate that street dust is the source of this pollution (Plak et al. 2010). The results of research on soils in Toruń (N Poland), a city of similar size to Lublin, show a lack of pollution in the case of I_{geo} and a significant enrichment of Pb and Cu in the case of EF (Charzyński et al. 2017).

As in the case of studies by other authors, no correlation was found between the intensity of motor traffic and heavy metal content (Charlesworth et al. 2011). It should be noted that such data for locations with the highest level of pollution with street dust were not available. Only in the case of Cu, a correlation was identified between its content in street dust and the network of aboveground power cables made of copper. Increased Cu levels occurred in locations with a high intensity of trolleybus traffic.

Further research is needed on the seasonal variation of the content of the heavy metals, multi-year trends as well as their content in different sizes of dust particles. It should also be remembered that the individual indices show slightly different pollution levels, even though the general trends for the specific elements are maintained in Lublin's street dust. The problem of improving the method of calculating the indices requires further study.

Conclusions

The level of street dust contamination with heavy metals in Lublin, determined based on five geochemical indices, is generally low. Only the pollution index reaches values indicative of considerable pollution in the case of some elements. Pollution with Cr and Ni does not occur. Samples are characterised by moderate pollution or a lack of pollution with Pb and Zn, although increased Zn levels occurred in some samples. The most significant pollution was found in the case of Cd and Cu in some samples. Particularly, for Cd, a highly toxic element, the pollution of street dust in Lublin should be regarded as a major health problem. Heavy metal levels in street dust are distinctly higher in comparison with their levels in the soils in Lublin. Thus, higher levels of elements from this group indicate their anthropogenic source. It should be stressed that the highest concentrations of Cd occurred within the main thoroughfare of the city. There was a distinct correlation with the presence of trolleybus wires in the case of Cu and the presence of industrial plants in the case of Zn.

The results of statistical methods (correlations, PCA, and CA) and the analysis of the spatial pattern of pollution indicate the possibility of distinguishing the following groups of elements and their origin in street dust: (1) Fe, Mn, Cr, Ni, (2) Pb, (3) Cd, Cu and Zn. The influence of natural and anthropogenic factors can be identified as a source of heavy metals in the case of group (1). Among these factors, the delivery of mineral material linked with winter road maintenance as well as redeposition of street dust are predominant. In group (2), anthropogenic influences (vehicular emissions) are predominant but natural delivery occurs as well. In group (3), anthropogenic delivery (vehicle emissions, brake linings) is predominant.

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